ARMY RESEARCH LABORATORY

Progress Report for the Robotic Intelligence Evaluation Program Year 1: Developing Test Methodology for Anti-Rollover Systems

by MaryAnne Fields

ARL-TR-3811 **June 2006**

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14. ABSTRACT

The Robotics Intelligence Evaluation Program (RIEP) is a joint effort by the U.S. Army Aberdeen Test Center (ATC) and U.S. Army Research Laboratory (ARL) to develop methodologies to evaluate robotic behavior algorithms that control the actions of individual robots or groups of robots acting as a team to perform a particular task. Although vehicle chassis performance will impact the evaluation of robotic behavior algorithms, testing of intelligent robotic platforms requires more than the classic automotive tests. The tests and procedures required to evaluate these algorithms cross the traditional boundaries between operational and developmental testing and between hardware and software testing. This document is a discussion of an anti-rollover case study used to refine the RIEP methodology. We begin with a discussion of vehicle rollover and prevention systems. Most of the information for these sections comes from the automotive industry where anti-rollover technologies are becoming important safety features. We discuss the current measures and tests used by automotive safety engineers and some of the additional elements that need to be considered for robotic systems. We also discuss several simulation tools applicable to vehicle rollover studies. Finally, we make recommendations for virtual and physical tests of anti-rollover systems.

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1. Introduction

The Robotics Intelligence Evaluation Program (RIEP) is a joint effort by the U.S. Army Aberdeen Test Center (ATC) and U.S. Army Research Laboratory (ARL) to develop methodologies to evaluate robotic behavior algorithms that control the actions of individual robots or groups of robots acting as a team to perform a particular task. Although vehicle chassis performance will impact the evaluation of robotic behavior algorithms, testing of intelligent robotic platforms requires more than the classic automotive tests. The tests and procedures required to evaluate these algorithms cross the traditional boundaries between operational and developmental testing and between hardware and software testing. Developmental testing evaluates behavior algorithms using performance specifications contained in the relevant system contract. However, these specifications define parameters such as chassis performance, sensor detection levels, and low level behaviors which might include maximum on-road speed, minimum obstacle height detection, maximum range at which system can detect a human-sized obstacle, and so on. Specifications for higher level behaviors will likely be less well defined. In some sense, evaluating behavior algorithms is similar to evaluating new tactics, techniques, and procedures (TTPs) for manned systems. Battlefield simulation tools are generally used to allow researchers to look at the effect of TTPs on combat performance measures, and these same tools are key to the evaluation of intelligent robotic systems. Behavior algorithm performance is affected by software design as well as vehicle design, but these algorithms are generally driven by on-board sensors and external information sources such as human operators or situational information systems that supply the input that determines specific actions within the behavior algorithm.

There are four aspects of the RIEP process. First is a thorough analysis of the task addressed by the behavior algorithm. Once the task is understood, the second aspect of the methodology is to find a simulation environment that is “rich” enough to simulate the task and test the proposed algorithm. The third aspect of RIEP is to determine a suitable method to link the proposed algorithm to the simulation environment. The last aspect of the program is to design a set of meaningful tests and performance measures to evaluate a proposed behavior algorithm.

The first step of the REIP process is a thorough analysis of the task addressed by the behavior algorithm. The emphasis is on the *task*, not the algorithm, since many algorithms can be proposed to solve a specific task. Behavior algorithms are being designed to perform tasks ranging from system health monitoring to battlefield missions such as area reconnaissance. The four-dimensional real-time control system (4D-RCS), an architecture for designing robot control systems, provides a convenient way to rank task complexity and to look at the resolution of information required by each task. Figure 1 provides a diagram of the 4D-RCS architecture. Each level of the architecture contains three components: an executor that accepts plans and information from the next higher level; a planner that directs the actions of the robot and sends

tasks to the next lower level; and a world model that contains sensor information. At the servo level, the robot controls the actuators that move the vehicle and subsystems such as cameras on board the robot itself. The robot acts quickly, typically on a microsecond scale, on information provided by on-board sensors. The primitive level involves low-level vehicle tasks such as obstacle avoidance, image processing, etc. The subsystem level combines tasks into important activities, such as autonomous mobility or reconnaissance. At the vehicle level, the robot performs functions that are tactically useful on a battlefield. At the section level, these functions extend to include tasks that are performed by groups of robots. The 4D-RCS continues beyond the levels shown in figure 1; the higher levels resemble levels of military organizations.

Tasks can involve multiple levels of the 4D-RCS structure. For instance, a reconnaissance mission is a section-level task that involves a team of robots that provides information about a designated area of the battlefield. Each robot performs independent vehicle-level behaviors that contribute to the overall mission. These vehicle-level tasks can be subdivided into three distinct subsystems: mobility, sensing, and weapon control. Autonomous mobility involves map-based planners and obstacle-avoidance systems. Autonomous sensing may involve several sensors and fusion algorithms that combine information from multiple sensor sources. Once we understand the task, we can identify critical elements of the environment needed to support an evaluation of algorithm designed to address the task. Generally, we need to consider terrain topography, composition, surface features, weather elements such as wind and rain, and the simulation tool. The world-model blocks from figure 1 provide a rough estimate of the level of detail required to stimulate tasks at each level of the architecture. Section-level behavior tasks depend on very crude information such as the location of lakes or canopy areas. At the subsystem level, tasks depend on detailed environmental information such as the location of ditches and individual trees. The primitive level requires even more detail, such as the location, shape, and composition of terrain features.

The choice of the simulation tool can also be tied to the 4D-RCS structure. Effective testing of section-level behaviors requires a simulation tool capable of representing the position of individual vehicles and modeling engagements between two or more forces. Also, it may be desirable to model at least some of the command and control (C2) structure for the unit that executes the behavior algorithm. Sensor information is represented as polygonal and linear "map" features that become known as the vehicle moves around in the simulated world. Subsystems such as the autonomous mobility system require simulation tools that can model the position and orientation of each vehicle. Sensor models provide information about the immediate vicinity of the vehicle. Visual sensor performance models interact with objects approximately 10 to 20 inches in radius. The primitive level requires tools that can model the position and orientation of vehicle components. At this level, it becomes important to model the process of sensing the environment.

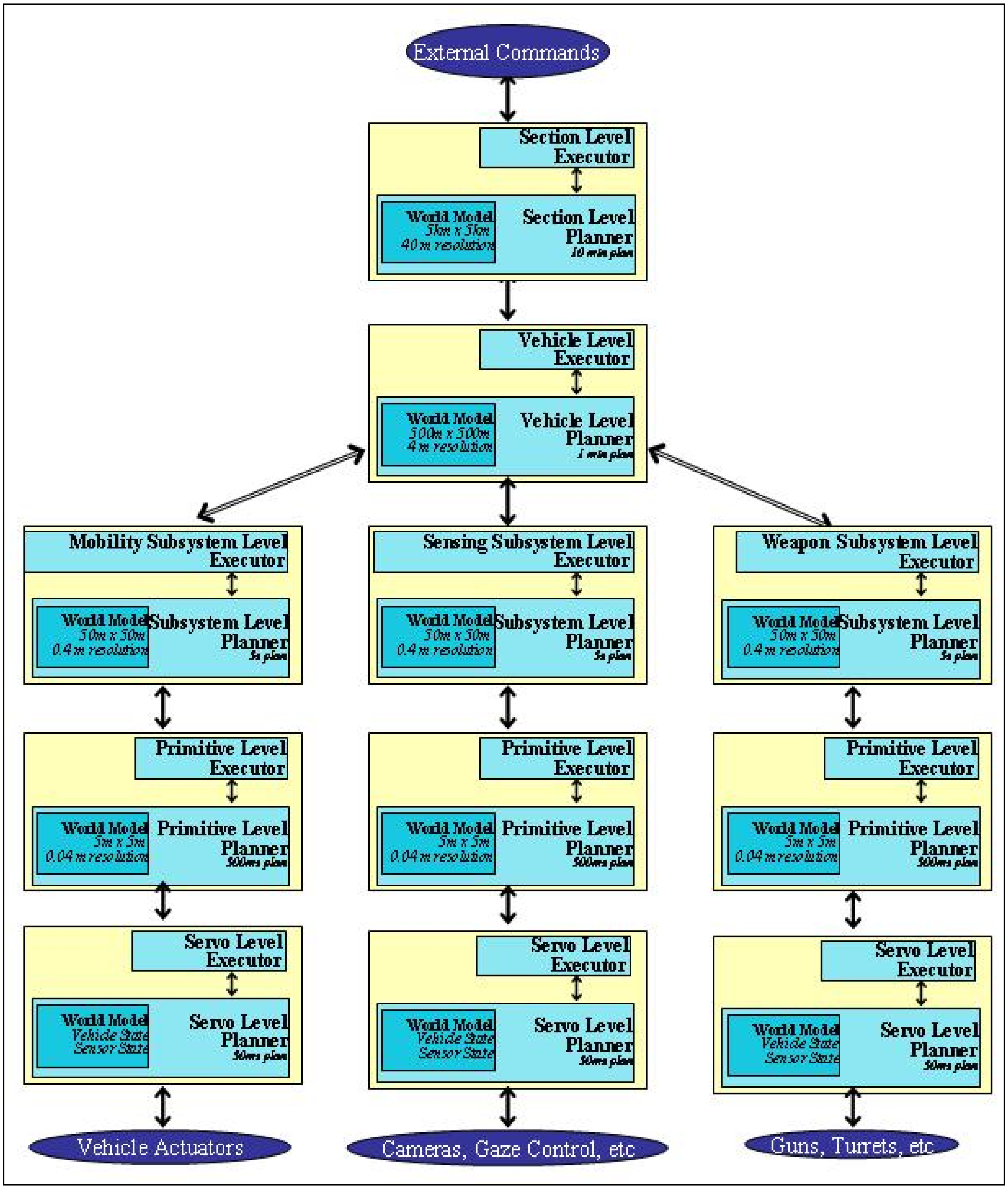

Figure 1. The 4D-RCS robotics control architecture.

Linking the behavior algorithm that is undergoing test to the virtual world can be accomplished in two ways. The first, a dissection approach, is to rewrite the behavior algorithm as an element of simulation tool used in the analysis. If this approach is carefully executed, it leads to detailed understanding of the algorithm undergoing test, the sensory information required to drive the algorithm, and the relationship between the behavior algorithm and the host robotic platform. This approach is useful in building a behavior algorithm for complex force-on-force models. It is

also useful for modularized behavior algorithms that can be separated into component parts with the 4D-RCS architecture as a guide. As a module in the behavior is changed, that module of the simulation can be revised. Researchers can use these systems to study the response of high-level behaviors to different levels of performance of the sub-behaviors. To be successful, this approach requires close collaboration between the behavior developer and the behavior evaluator.

The second method, a “black box” approach, is to link the behavior system embedded in the robot with the virtual environment. Often, this is the preferable approach since the algorithm cannot be modified during the process. Figure 2 shows a graphic that illustrates this approach. The behavior algorithm in the middle block is the system undergoing test. Information from the virtual world provides the behavior algorithm with simulated sensor input. Sensor models in the virtual environment must be capable of supplying sensor information at the level of detail required by the behavior algorithm. Commanding entities provide C2 information by providing orders, routes, and situational awareness overlays. Information also flows from the behavior algorithm to other entities in the exercise. Both of these connections depend on a communica-tion model that models the flow of information in and out of the behavior algorithms. The key to success for this approach is to define the interfaces between behavior algorithm and the virtual environment.

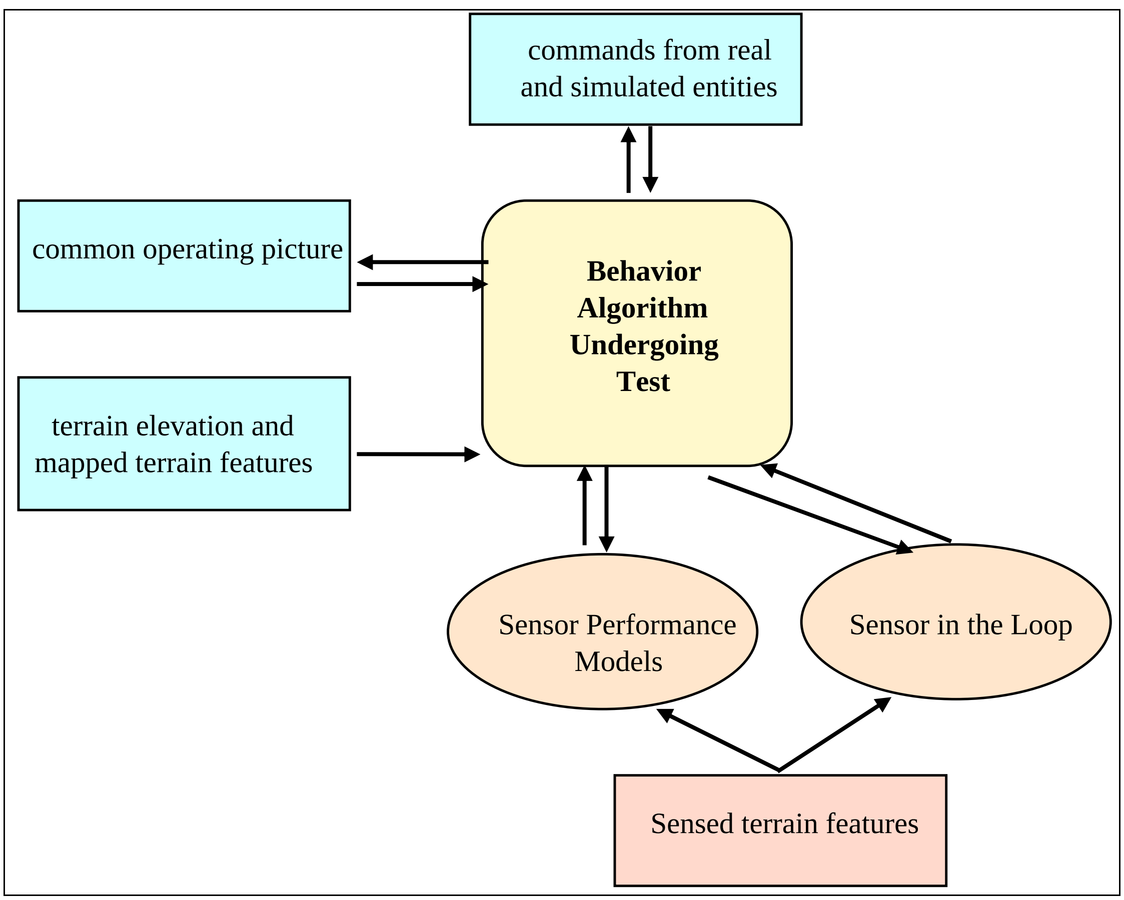

Figure 2. Embedding a behavior algorithm in a virtual environment.

The last step of the RIEP is to design a set of meaningful tests to characterize behavior algorithm performance in battlefield environments. Test scenarios need to include environmental challenges that allow researchers to assess the robustness and reliability of the behavior algorithm undergoing test. Testing low-level behavior algorithms such as autonomous mobility, resembles traditional testing, i.e., the virtual environment is populated with specific features designed to test the response of the system. Often, these tests can be tied directly to a contract specification or to an operational requirements document (ORD). Higher level behaviors need to be tested in the context of force-on-force scenarios. ORDs and contract specifications are often vague about performance expectations for high-level behaviors, so it is useful to examine a series of force-on-force scenarios designed to find performance limitations. Early in the development cycle, well-designed force-on-force scenarios can help focus the development effort on frequently occurring issues and away from rarely occurring issues. One issue that needs to be addressed with high-level behaviors is the behavior undergoing test. One approach is to regard a test of a high-level behavior as a test of all the underlying algorithms. Since most of the subsystems are not yet finalized, we may need methods to isolate the performance of high-level algorithms from the lower level algorithms.

The RIEP process is being refined through a series of case studies, beginning with subsystem-level behaviors and ending with the evaluation of a mixed human-robot reconnaissance behavior. In this first year of the process, we have chosen to examine vehicle rollover prevention algorithms. Rollover prevention is critical for the safety of manned and unmanned systems. It is also specified by the ORD for some near-term robotic systems.

The remainder of this document is a discussion of the progress of RIEP during the first year. We begin with a discussion of vehicle rollover and prevention systems. Most of the information for these sections comes from the automotive industry where anti-rollover technologies are becoming important safety features. Sections 4 and 5 discuss the current measures and tests used by automotive safety engineers and some of the additional elements that need to be considered for robotic systems. We discuss several simulation tools applicable to vehicle rollover studies. Finally, we make recommendations for virtual and physical tests of anti-rollover systems.

2. Vehicle Rollover

Although we consider primarily “car-like” robots on relatively flat surfaces in this research, it is useful to provide a general definition of vehicle rollover that applies to traditional wheeled and tracked vehicles as well as vehicles with legs, large mobile manipulators, outriggers, or other novel characteristics operating in a wide variety of terrains. Consider an arbitrary ground vehicle that has *n* points of contact with the ground. These *n* contact points form a support polygon for the ground vehicle. A rollover or “tip-up” occurs when the vehicle’s center of gravity (c.g.)

moves far enough outside the support polygon to cause the vehicle to rotate around one of the polygon sides (Papadopolos & Rey, 1996). In automotive applications, cars typically roll laterally around either the left or right set of wheels.

Dynamic rollovers can be divided into two classes: tripped and untripped. Tripped rollovers are initiated by a mechanism such as a curb, guardrail, soft soil or road edge. Tripped rollovers are often preceded by a loss of vehicle control that allows the vehicle to leave the road surface. Untripped rollovers are initiated by vehicle maneuvers on a normal road surface. According to the National Automotive Sampling System Crashworthiness Data System (NASS CDS) maintained by the National Highway Traffic Safety Administration (NHTSA), less than 5% of the rollover crashes are untripped (Hertz, 1999). Despite their low frequency of occurrence, much of NHTSA's research efforts focuses on developing extreme steering maneuvers to test untripped rollovers (Forkenbrock, Garrott, Heitz, & O'Harra, 2002; Forkenbrock, O'Harra, & Elasser, 2004; Howe, Garrott, Forkenbrock, Heydinger, & Lloyd, 2001). Untripped rollovers are directly related to controllable factors such as vehicle design and driver behavior. Tripped rollovers are also related to vehicle design and driver behavior, but any vehicle will roll over if it impacts a suitable tripping mechanism with sufficient lateral velocity.

3. Rollover Prevention

Unmanned systems are still in the development stage of their life cycle. Consequently, we do not have a specific anti-rollover system to test. However, anti-rollover systems developed for ground robots are likely to be similar to those developed for the automotive and commercial vehicle industries. These industries are very interested in developing methods to predict and prevent vehicle rollover. Their development efforts include "driver-based" strategies designed to reduce the probability of encountering a near-rollover condition and vehicle-based systems such as rollover warning sensors, suspension system components such as anti-roll/sway bars and vehicle stability control (VSC) systems designed to recover from a near-rollover condition. Each of these efforts is potentially applicable to unmanned systems.

Rollovers can be prevented by training drivers to maintain vehicle control. Tire maintenance affects the controllability of the vehicle. Cargo loading strategies can change the c.g. affecting rollover propensity. Drivers can be taught emergency maneuvers that help them maintain control of the vehicle. Some driver education translates to the control of unmanned vehicles. Vehicle maintenance and loading is similar for manned and unmanned systems. For tele-operated systems, the operator can be trained to avoid excessive speed and steering. For autonomous systems, the robot planning algorithms can consider vehicle stability as a factor as it plans its path.

In the last decade, many groups have begun to develop rollover warning systems for passenger and commercial vehicles. Under the Intelligent Highway Program, "smart" signs can warn

trucks of impending rollover by measuring the speed of the truck. Chen and Peng (1999) have developed a time-to-rollover warning algorithm that can warn drivers of impending rollovers, based on the vehicle yaw rate. Rey and Papadopoulos (1997) have developed a warning algorithm applicable to forestry equipment with booms, cranes, or other manipulators. Automobile manufacturers have also developed rollover sensors. However, most of these sensors are used to determine when protective devices such as air bags should be deployed to protect the vehicle occupants. Warning systems can allow operators of tele-operated systems to correct unsafe vehicle operations. They could also provide an audio or visual rollover warning to troops in the vicinity of an unmanned system. The sensors and algorithms of the rollover warning systems can be incorporated into autonomous planning systems.

Suspension system components such as anti-roll or sway bars control the body roll in cornering maneuvers. Another vehicle design technology (active rear steering) is designed to increase vehicle maneuverability at high speeds. Hac (2002) examined the effect of these vehicle design choices on rollover propensity.

VSC systems are designed to assist drivers in maintaining steering control of their vehicles. These systems use yaw rate sensors to compare the actual path of a vehicle to its intended path. Automatic braking can be applied independently to each wheel to compensate for excessive oversteer or understeer. VSC indirectly prevents rollover by keeping the vehicle on the road surface. There are some new (2005) systems that attempt to directly prevent untripped rollover by incorporating roll rate and lateral acceleration sensors. Again, the control mechanism is to decelerate the vehicle and to reduce the sharpness of the turn. Unmanned systems can benefit from VSC technology. Tele-operated systems could use the technology to compensate for system latency, lack of driving awareness, or over-eager operators. Autonomous systems could use VSC technology to monitor and adjust the vehicle yaw rate; this may be particularly important on loose soil or ice-covered surfaces.

4. Current Measures and Tests

Highway rollover crashes are a major safety concern. Consequently, automotive safety engineers in NHTSA, the automotive industry, insurance industry, and consumers’ groups have developed tests designed to measure the rollover propensity of passenger and commercial vehicles. Their concerns as they develop these tests are similar to ours, namely, test repeatability, relevance to real driving issues, and crash rate predictability. Some of the tests are static measures based on vehicle parameters such as vehicle weight and the location of the c.g. Newer tests are dynamic maneuvers designed to look at vehicle performance in a series of maneuvers designed to mimic worst case emergency maneuvers.

A common measure of rollover propensity is the static stability factor (SSF). This measure is derived from the physics of rigid bodies. Consider a vehicle to be a rigid body with mass *m* and width *t* moving along an arc of radius *r* at a speed *v* on a flat surface. Suppose that the height of the c.g. for this vehicle is *h*. The vehicle rolls on its side if the lateral forces given in the right-hand side of equation 1 exceed the vertical forces given on the left-hand side.

$$mg\left(\frac{t}{2}\right) = \frac{mv^2}{r}h \tag{1}$$

Rearranging equation 1 provides the definition for the SSF:

$$\frac{t}{2h} = \frac{v^2}{rg} \tag{2}$$

The left-hand side of equation 2, which is defined to be the SSF, depends only on measurable vehicle parameters: the c.g. and vehicle width. The right-hand side of the equation gives a practical safety formula specifying safe combinations of speed and turn radius. Points along the spiral path shown in figure 3 have been labeled with the rollover speeds for two different values of the SSF. The circled numbers indicate the turn radius of the spiral path in meters. The blue numbers indicate rollover speeds for vehicles with SSF = 1.0. The red numbers indicate rollovers for a vehicle with SSF = 1.5. Figure 4 shows a size comparison between vehicles with SSF = 1.0 and SSF = 1.5.

Equation 2 applies to vehicle on flat ground. A more general equation relates the lateral acceleration to the SSF and the side slope angle, ϕ.

$$\frac{\mathrm{SSF} - \tan\varphi}{\mathrm{SSF}\ \tan\varphi + 1} = \frac{v^2}{rg} \tag{3}$$

Other static rollover propensity measures are the tilt table ratio (TTR), the side pull ratio (SPR), and the critical sliding velocity (CSV). In the tilt table test, the vehicle is placed on a table and tilted laterally until the front and rear wheels on the uphill side lift. The tangent of the longitudinal table angle is the TTR. The SSR is the ratio of the vehicle weight to the lateral force required to cause two-wheel lift. The CSV is lateral velocity required to cause two-wheel lift when the vehicle strikes a tripping obstacle such as a curb. It can be computed with the use of the vehicle mass, M, the vehicle width, T, the height of the c.g., H, and the roll moment of inertial about the c.g., I_{xx} (Heydinger et al., 1999).

$$\mathrm{CSV} = \sqrt{\frac{2gI_{oxx}}{MH^2}\left(\sqrt{\frac{T^2}{4} + H^2} - H\right)}, \tag{4}$$

with

$$I_{oxx} = I_{xx} + M\left(\frac{T^2}{4} + H^2\right). \tag{5}$$

Huang (Huang, 2002) has a detailed derivation of the CSV equation.

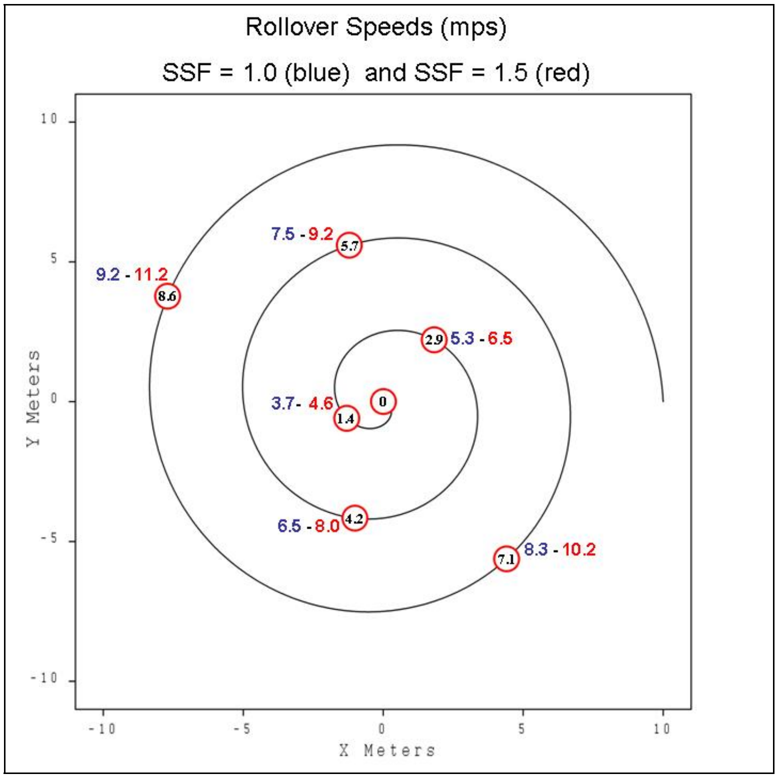

Figure 3. A spiral path showing the required rollover velocity.

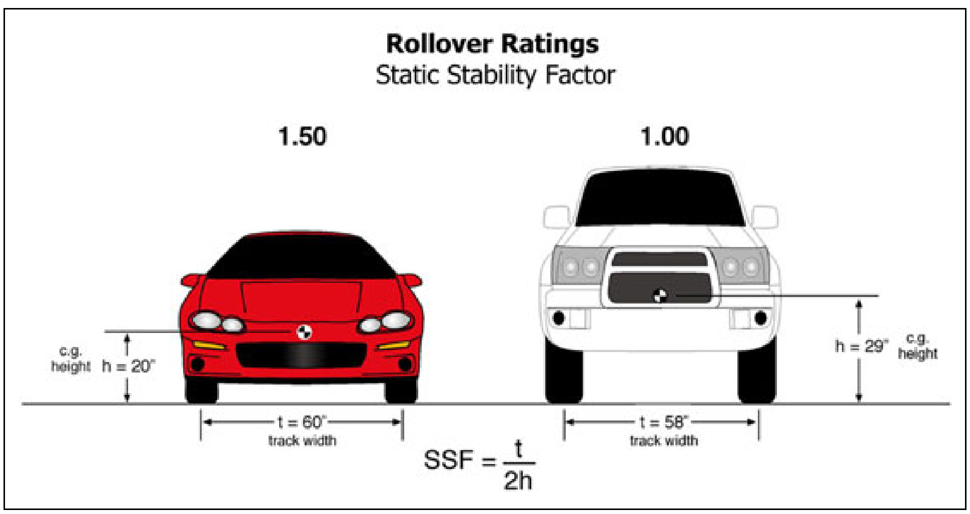

Figure 4. Hypothetical vehicles with SSF = 1.5 and SSF = 1.0 (NHTSA, 2005).

Since the static measures can be collected in laboratory settings, these tests are considered very repeatable. However, these measures, especially the SSF, have been criticized for being too simplistic. The SSF and the CSV treat the vehicle as a solid block, giving no credit to the stabilizing influence of the suspension system. There is also some concern that manufacturers

can optimize their vehicles to “score” well on the CSV without any improvement in the safety of the vehicle (NHTSA, 2004). Since they are static measures, they cannot be used to evaluate the performance of VSC systems. However, the SSF correlates well with existing accident statistics. Also, according to NHTSA, the static measures are the best predictors of vehicle performance during a potential trip.

Dynamic rollover propensity maneuvers allow the vehicle performance to be tested *in situ*. They allow the complex interactions between the suspension system and the vehicle chassis and environmental factors such as road surface and cross winds. Test maneuvers can also evaluate the effect of VSC systems on vehicle rollover. However, the very elements that make test maneuvers relevant to real-world driving make repeatability difficult. Right now, there is not enough data to determine the relationship between driving maneuver performance and rollover accident statistics.

The driving maneuvers used by automotive safety engineers include slowly increasing steer, j-turn, and fishhook (Howe, Garrott, & Forkenbrock, 2001). In a slowly increasing steer maneuver, the driver keeps the speed constant and gradually increases the steering wheel angle. In a related maneuver, the steering wheel angle is held constant while the speed is gradually increased. The primary use of these maneuvers is to characterize the responsiveness of the vehicle and to determine the maximum obtainable lateral accelerations. The j-turn is a sudden large turn similar to the maneuvers required to negotiate a cloverleaf ramp. The fishhook maneuver involves a large steering wheel angle change followed by a large steering wheel angle change in the opposite direction. It is analogous to maneuvers to avoid obstacles in the roadway.

The use of steering and braking machines increases the repeatability of the maneuver tests. Performing these maneuvers on a test track is still a risk to the drivers and the vehicles. Roadway simulators such as the one at ATC can reduce risk to the test article and human participants and increase test repeatability (Connon, 2005).

Crashworthiness studies use tests designed to deliberately induce a rollover. These include driving onto corkscrew ramps, sliding into tripping hazard such as posts or gravel pits, or driving into a hole. A common use for these tests has been to examine occupant safety. Recently, Viano and Parenteau (2004) have developed a series of tests to define rollover sensor requirements for applications such as air bag deployment. According to their research, the results of these instrumented repeatable tests mimic about 90% of real-world rollover situations.

5. Roll-Over Testing for Robotic Systems

The previous section described tests applicable to passenger vehicles driven on highway systems. These tests are applicable to robotic systems, but there are additional factors that need to be

considered for robots. Situational awareness, communication delays, perception, and path planning all have a potential impact on rollover propensity.

The robots considered in this research are either tele-operated or autonomously driven. Each of these control mechanisms has its own challenges with respect to evaluating rollover propensity. Tele-operated systems depend on the human operator to perceive and avoid navigational hazards. These systems require a very-high-bandwidth, low-latency, and highly reliable communications system. Delay in the communications system, coupled with the limited perception available to the operator, can lead to vehicle rollover. A study of tele-operated system accidents from early 1990s found that 60% of the accidents were rollovers (McGovern, 1991). Generally, the operators had only limited awareness of the vehicle orientation and were unable to sense near-rollover conditions before they became irreversible. More recent work in the field of urban search and rescue (USAR) robots found that situational awareness remains an important issue (Burke, Murphy, Coovert, & Riddle, 2004).

Autonomous systems use planners to process *a priori* information such as digital maps and acquired information such as sensor readings to navigate. In systems using hierarchical control architecture, the planner is divided into subsystems that operate at different frequencies. The mission planner translates the overall mission objectives into tasks and specific destinations for the robot; the mission plan is revised infrequently as the mission changes. The navigator does global path planning based on an *a priori* map and situational awareness information; paths are replanned as tactical information (such as known enemy positions) changes. The pilot does moment-to-moment trajectory planning. It monitors current position and pose (roll, pitch, yaw) using a variety of means such as an IMU (inertial measurement unit), GPS (global positioning system), and odometry with estimates from all, combined by a Kalman filter or something similar. Trajectories change frequently as the perception system acquires new information about the environment (Board on Army Science and Technology [BAST], 2002).

Figure 5 shows a contour map and three of many possible paths between points A on the upper left edge of the map and point B in the lower right region of the map. A robotic system chooses the “best” path by minimizing the cost of each path. Costs include travel time, exposure to known enemy positions, vehicle safety, and other factors. In this example, the red path may minimize exposure to an enemy in the upper right area of the map, but it may not be safe for the robot to travel along the steep contours of the hills. Plans evolve, as the blue and green plans illustrate. In this illustration, the blue path incorporated additional sensor information that became available when the robot reached the middle of the map.

Path planning decisions can impact rollover propensity. Planners that do not incorporate system safety into the cost function may be more likely to roll than planners that consider vehicle orientation as a cost variable. Exercising the planners on a variety of realistic battlefields allows researchers to evaluate the rollover sensitivity of the planning process.

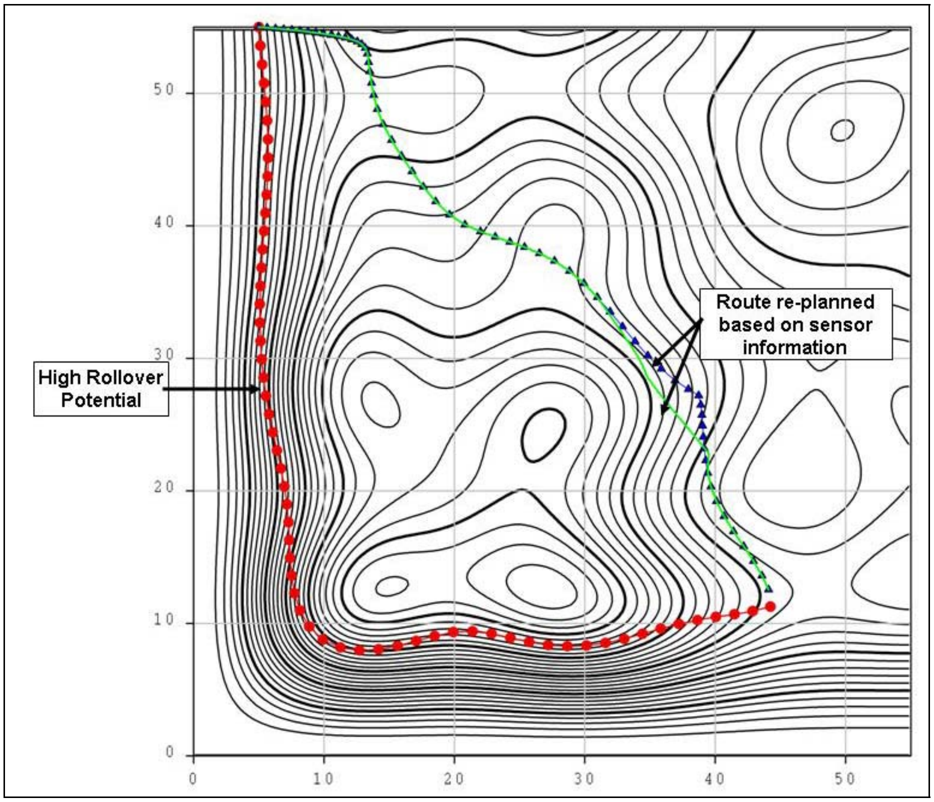

Figure 5. Paths between point A at the upper left edge of the map and point B in the lower right region of the map.

6. Simulation Tools

Modeling and simulation programs are becoming common tools in automotive safety engineering. In this section, we discuss the use of simulation tools to supplement the laboratory measurements and field testing for rollover propensity. Three common simulation tools, PC-Crash[1], TruckSim, and CarSim[2], are used in the rollover literature. We also discuss two tools developed specifically for military use: Vehicle Dynamics Mobility Server (VDMS) and One Semi-Automated Forces (OneSAF). VDMS is similar to the commercial automotive simulation packages used in the literature. OneSAF is a battlefield simulation tool.

PC-Crash is a momentum-based simulation tool which is used in accident reconstruction. It can simulate scenarios involving as many as 32 entities including cars, trucks, pedestrians, and bicyclists. Vehicles are described by geometric properties such as size, weight and the c.g., suspension properties such as stiffness and tire characteristics, power train properties, and

[1]PC-Crash is a trademark of Dr. Steffan Datentechnik Ges.m.b.H.
[2]TruckSim and CarSim are trademarks of Mechanical Simulations Corporation.

moments of inertia. Aspects of the simulated environment such as wind speed, obstacle locations, and road surface characteristics can be modified. In addition, PC-Crash has two different driver models to control the vehicles. Often, PC-Crash is combined with a finite element model (e.g., LS-DYNA[3], MaDymo[4], and PAM-Crash[5]) to look at vehicle and occupant damage.

Viano and Parenteau (2004) used PC-Crash to help develop test procedures and equipment to support their work on rollover sensors. This tool was used to simulate various tripped rollover maneuvers and to set experimental parameters such as impact speed and driving conditions for the field rollover tests. Since this tool is often used in court cases, there have been several validation studies. Cliff and Montgomery (1996) conducted some early validation studies. Later, Cliff and Moser (2001) compared PC-Crash results to staged vehicle crashes. Recently, Gopal, Baron, and Shah (2004) published some initial validation studies comparing PC-Crash results to controlled laboratory rollover tests.

CarSim and TruckSim have been used for more than 20 years to study the dynamics of automobiles and trucks. CarSim simulates the dynamic behavior of race cars, passenger cars, light trucks, and utility vehicles. Typically, a vehicle is described as a 14-degree-of-freedom (DOF) system. The chassis has three rotational and three translational degrees of freedom, and each wheel can rotate on its axle and move vertically. TruckSim is a similar product designed for analyzing commercial trucks and articulated vehicles. New vehicle models are created with the CarSim-TruckSim user interfaces provided by the simulation package or by models created with the MATLAB[6] and SIMULINK packages commonly used as design tools in the automotive industry. The road surface can be modified to represent many different environments, including off-road areas.

Since CarSim is a multi-component model, it has been used to study the interactions of the suspension systems with the chassis (Sharp & Bettella, 2001). By linking the vehicle model with external simulation tools, other researchers have used the simulation to develop vehicle stability control algorithms and sensors (Eisele & Peng, 2000). Anwar (2004) used the model to develop a traction control algorithm. Chen and Peng have used it to investigate rollover warning systems for trucks. It has been linked to motion simulators and it can support human driver studies.

Ungoren, Peng, and Tseng (2004) have also used CarSim to iteratively develop a series of worst case maneuvers to test vehicle stability control systems for sport utility vehicles.

There have been some validation studies as well. Alonso provides a comparison between a general 14-dof vehicle model and field maneuvers (Alonso, 2005). Ungoren et al. (2004) compared the performance of a TruckSim Jeep Cherokee model to field data for banked turn

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[3]LS-DYNA is a trademark of Livermore Software Technology Corp.
[4]MaDymo is a trademark of the Netherlands Organization for Scientific Research.
[5]PAM-Crash is a trademark of the ESI Group.
[6]MATLAB and SIMULINK are registered trademarks of the MathWorks.

maneuvers. Kalwauchi et al. (2005), found a favorable comparison between CarSim models and actual car performance on an oval test track.

Another simulation tool to consider is Tank-Automotive and Armaments Command (TACOM)-TACOM Research, Development, and Engineering Center (TARDEC's) VDMS (Brudnak, Nunez, & Reid, 2002). VDMS represents a vehicle as a 6-DOF chassis and four vehicle corners that represent the wheels and suspension system components at each wheel. New vehicle models are created by commercial packages such as SimCreator or MATLAB or SIMULINK. VDMS represents several aspects of vehicle dynamics including power and traction limits on mobility because of terrain slope and composition, vibration effects because of surface roughness, and vehicle instabilities such as rollover. Vehicle control is provided by an external interface such as joystick for tele-operated systems or by external control algorithms for autonomous systems. The model operates at 200 to 500 Hz which could support interactions with vehicle attitude sensors and anti-rollover algorithms that must operate quickly to stabilize the vehicle. VDMS can be used as a stand-alone model or as part of a distributed modeling environment. VDMS is a component of the Modeling Architecture for Technology and Research Experience (MATREX) federation of models developed by the U.S. Army Research Development and Engineering Command. VDMS was used as the mobility thread in the distributed test environment demonstrations (DTE4 and DTE5).

VDMS is part of the high-fidelity ground platform and terrain mechanics modeling (HGTM) science and technology objective (STO) to develop high fidelity, real-time, ground platform mobility and terrain models. As a part of this effort, TARDEC and the Army Corps of Engineers are developing tire-soil interaction models which will better represent tire slippage and sinkage (Richmond, Jones, Creighton, & Ahlvin, 2004).

Another tool to consider is Virtual.Lab by LMS[7] Engineering Solutions. Virtual.Lab Track Motion delivers powerful simulation capabilities specifically developed for track vehicle engineering. With Virtual.Lab Track Motion, engineers can assess the interaction of the vehicle with different terrain profiles to (a) study stability on a slope, in acceleration, in braking, or in lane changing (b) evaluate the vehicle's handling, and (c) optimize driver and passenger comfort. The solution computes the loads between track links and suspension parts and on vehicle bodies. It also gives guidance to the spring and shock absorber properties and to the optimal location of road wheels, idlers, sprockets, etc.

OneSAF test bed baseline (OTB 2.0) is an entity-level battlefield simulation tool used by many groups in the U.S. Army. The behavior of each entity is controlled by a collection of function libraries that handle low-level functions such as movement, sensory processing, or weapon control. Ground vehicles are represented as simple bodies having length, width, and mass with tracked or wheeled dynamics. The baseline OTB tool does not represent vehicle rollover; instead, the dynamics library limits maximum possible steering angle.

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[7]LMS is not an acronym.

While OTB and other battlefield simulation tools have limited value in developing engineering tests of vehicle rollover, they are important in determining the effect of vehicle rollover on overall system of system performance in realistic battlefield missions. As a part of our work, we extended a version of OTB 2.0 to allow vehicle rollover using the simple static stability relationship provided in equation 3. This rollover extension required the vehicle definition files to be modified to include the c.g. height. The side slope of the terrain was used as an estimate of vehicle yaw. Once the conditions for equation 3 are satisfied, the vehicle status changes from healthy to mobility killed. Figure 6 shows two similar vehicles executing a slowly increasing steering maneuver on flat ground. The vehicle on the right is more sensitive to rollover because it has a higher c.g. This maneuver is somewhat contrived, but with the SSF equation, researchers could investigate the effect of vehicle load on overall mission performance.

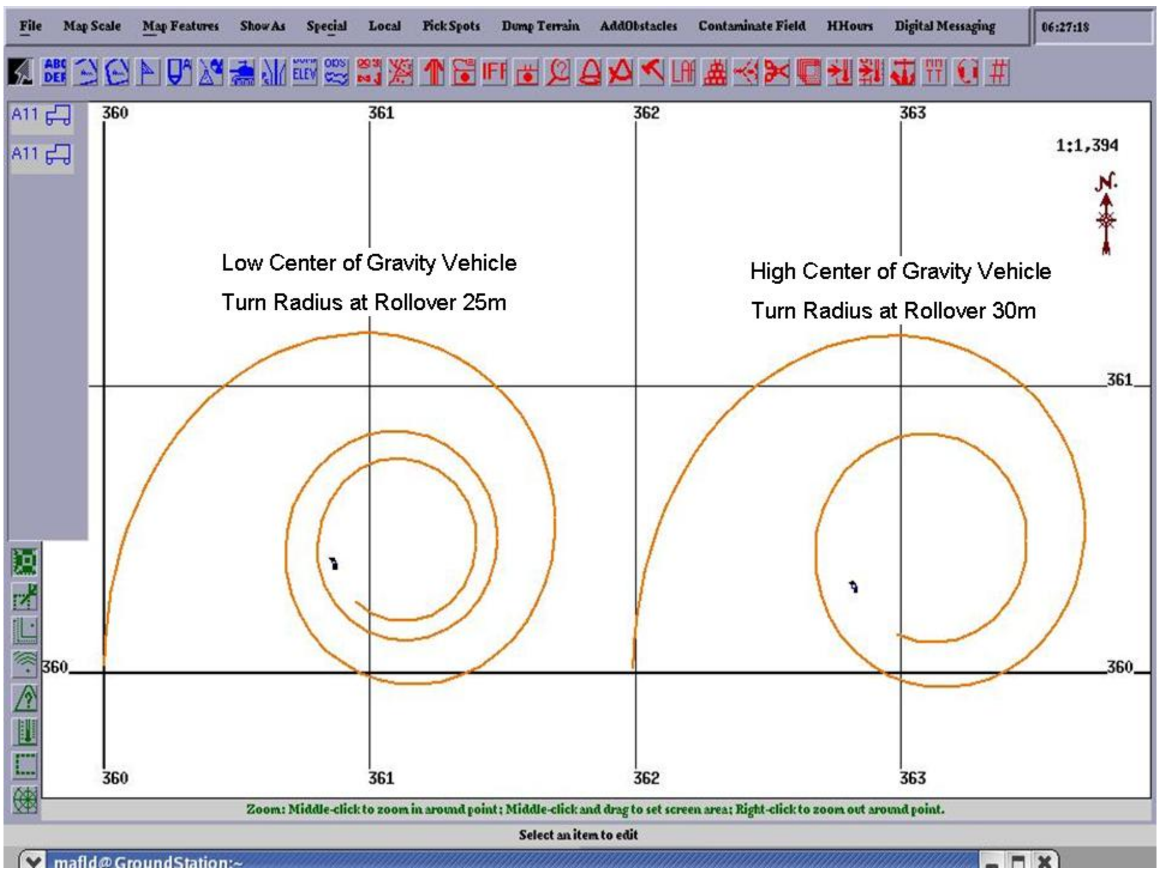

Figure 6. An OTB simulation comparing two similar vehicles executing slowly increasing steering maneuvers on flat ground.

The OneSAF Objective System is expected to be released in the spring of 2006. It is expected to use the Standard Mobility Model Application Programming Interface (STNDMob API). STNDMob API is being developed to consistently represent vehicle mobility for systems in battlefield simulations based on the North Atlantic Treaty Organization (NATO) Reference Mobility Model (NRMM) (Baylot et al., 2005). STNDMob provides reasonable speed limits for

vehicles based on vehicle type and the physical interaction between the vehicle and the terrain surface. STNDMob uses the SSF equations to determine the maximum safe speed.

7. Virtual Environment Requirements

In this section, we discuss the requirements that rollover modeling imposes on the virtual environment. We address two separate issues: simulating rollover propensity test maneuvers and simulating rollovers related to realistic battlefield driving.

The virtual environment required to simulate rollover propensity test maneuvers is relatively simple. In its most recent studies, NHTSA performed rollover propensity test maneuvers on a level test pad with a known, constant coefficient of friction. The digital terrain associated with each of the tools described in the previous section can support these rollover tests. It is possible to introduce variations into the basic maneuver tests by adding hills and other large terrain features. It is also possible to vary the surface composition. VDMS, OTB, and OneSAF store trafficability indices and terrain attributes for each elevation post in the terrain database. CarSim and TruckSim assign a friction map to the terrain surface.

Simulating rollovers related to realistic battlefield driving requires an analysis of future robotic mission profiles. In its 2002 study, the National Academy of Sciences stated that future Army mission profiles show that 70% to 80% of troop movement will use primary or secondary roads (BAST, 2002). Robotic systems are likely to have similar mission profiles requiring them to maneuver on and near road surfaces.

In OneSAF and OTB terrain databases, a road segment is a piecewise linear feature consisting of a collection of points on the battlefield, a road width, and soil type for the road surface (PEO STRI, 2004). CarSim and TruckSim databases describe roads as collection of geometry files specifying the three-dimensional (3-D) location of the road centerline and an elevation map of the road surface. The description also includes a friction map of the road surface. Open flight databases, used by the VDMS tool, can support detailed road descriptions with 3-D road geometry, and roadside features such as shoulders, curbs, and signs. In their crash maneuver work, Gopal, Baron, and Shah (2004) replicated various road geometries, road features such as curbs, and various surfaces such as asphalt, gravel, or loose soil using PC-Crash.

Robots commanded to follow the road, like automobiles on a highway, may occasionally leave the road surface because of obstacles in the roadway, lack of perception, or inaccuracies in the planning process. With a high fidelity representation of the roadway environs, researchers can investigate interaction with potential tripping mechanisms such as gravel shoulders, road edges, or curbs.

In an off-road environment, vehicles encounter terrain surfaces with different textures, roughness, and friction properties. In addition, mobility hazards such as holes and large rocks are more prevalent in an off-road environment. Battlefield simulation tools such as OTB and OneSAF use trafficability indices to determine speed, climb, and turning rate limitations over particular sections of terrain for each type of vehicle. The trafficability indices are derived from the NATO NRMM with the use of factors such as soil strength, vegetation, and terrain slope. Holes, rocks, fallen logs, and other potential tripping mechanisms are not generally represented in these terrain databases. However, it is possible to add tripping features to OTB terrain databases.

8. Perception Models

Simulations of test track maneuvers do not require sophisticated perception models. The vehicles drive the prescribed course on a smooth level surface that is assumed to be free of obstructions. However, for a robotic system operating in realistic settings, a rich virtual environment and a good dynamics model are not sufficient to represent a robot's behavior in a potential rollover situation. It is also necessary to model its perception of the environment. A suitable perception model represents the hazards that the robot "sees" with its perception system, the hazards it identifies, and the amount of time the perception process takes.

Robotic systems use a variety of systems to perceive the environment. These include scanning laser radar systems, visible and infrared cameras, acoustic sensors, and radar systems. First principle physics models of these sensors require the shape, composition and density of obstacles in the environment, atmospheric models, and models of the sensor information collection process. Such models do exist, but they require information that might be difficult to collect for a variety of battlefield environments.

Another approach is to model the "end product" of the perception system. This would be the information the robot uses to drive, such as a world map or, in the case of a tele-operated system, the information displayed to the operator as s/he remotely drives the robot. Such models provide the probability of detection for features in the environment as a function of obstacle range, orientation, vehicle speed, weather conditions, and other factors. Ideally, these models would be built with the use of data collected by organizations building robotic driving sensors. However, generalized functions could be used in conjunction with simulation studies to look at the sensitivity of rollover propensity to driving sensor performance.

9. Recommendations

In the previous sections of this report, we analyzed the rollover problem, identified some potential anti-rollover systems, and discussed virtual simulation tools that could be used in rollover research. In this section, we make some recommendations for a rollover testing program. We recommend three levels of testing. First, laboratory measures such as the SSF and the CSV provide insight into the inherent stability of the platform. On the sub-system level, we need tests to verify that the anti-rollover system works as the designer intends. More importantly, we need to establish the rollover propensity for the robotic vehicle, especially in the off-road environment where we do not have historic data.

At the subsystem level, we need to verify that the anti-rollover system triggers in time to prevent an accident. In the previous discussion, there were two levels of anti-rollover prevention: those connected with the vehicle that engage in a near-rollover condition and those connected with the "driver" that reduce the probability of encountering a near-rollover condition. Vehicle-based systems, including rollover warning sensors and differential braking systems, activate in response to unacceptable yaw or roll rates. The NHTSA maneuvers provide high yaw rates for stimulating the anti-roll system. Ramp and hill maneuvers that elevate one side of the vehicle could provide high roll rate stimulation. Note that these maneuver tests use steering machines and auto-pilots to ensure that vehicles drive the same path. Maneuvers along pre-determined paths do not provide useful information for "driver"-based systems such as terrain adaptive planning algorithms. Driver-based systems adjust the vehicle path to reduce the probability of encountering a near-rollover condition. Handling tests, such as the slalom maneuver shown in figure 7, in which the vehicle picks its own path are more suitable for testing these systems. Performing the vehicle-based and driving-based maneuvers on a test track increases the repeatability of these tests.

It is essential to protect vehicles and personnel during testing. Vehicle-in-the-loop systems such as ATC's Roadway Simulator offer a safe alternative to testing on tracks for wheeled vehicles that weigh more than 3000 lb. However, the roadway simulator must be supported by detailed vehicle models. Testing autonomous systems on the roadway simulator may be possible. Right now, an autopilot drives vehicle on the roadway simulator. For autonomous systems, that autopilot needs to be replaced with the robotic control system. The most challenging task will be providing artificial sensor information for the robotic sensing system.

Simulation tools are useful for testing vehicle-based and driver-based systems. As we pointed out in our earlier discussions, the automotive industry extensively employs simulation tools such as CarSim and PC-Crash to reduce the time and cost of its safety testing programs. These tools require detailed models of each vehicle and each anti-rollover system to be tested. These models can be built by the tester or supplied by the developer. Linking driving algorithms to simulation tools allows researchers to examine driver-based anti-rollover systems. For slalom tests,

simulation tools can help determine maneuver speeds and the spacing and width of the gates. By monitoring the driving algorithm during simulated test maneuvers, testers can examine the planning process.

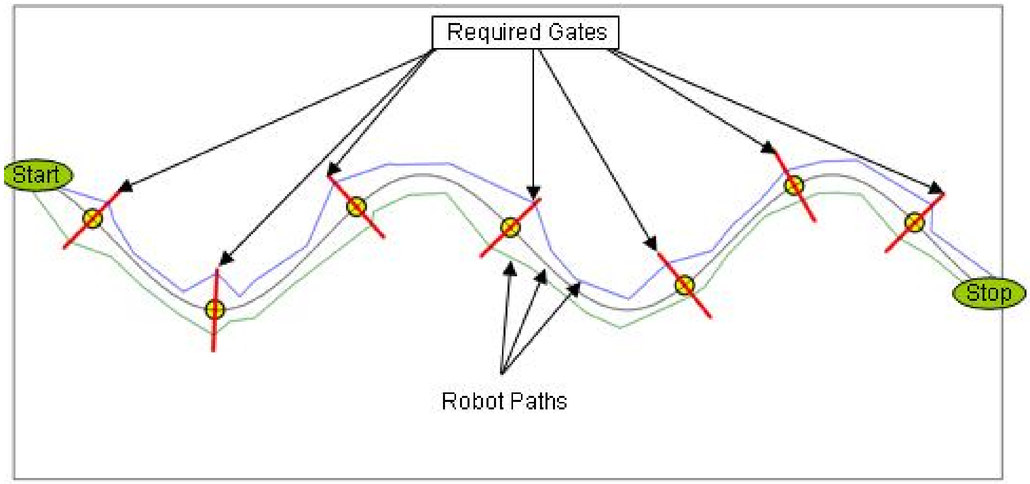

Figure 7. A conceptual slalom course to test autonomous systems.

Focusing on the subsystem level of testing may demonstrate that an anti-rollover algorithm functions properly on improved road surfaces, but it does not fully address performance in the complex off-road environment. Actual system-level performance is a combination of vehicle properties, driver skill, and the complexity of the environment. While this is certainly equally true for manned systems operating on roads, we cannot make the assumption that the surface is supposed to be flat and smooth and that there are "representative" maneuvers that can be tested. Rollover propensity, a measure of the probability that a system will roll during expected operating conditions, provides system-level performance information that testers can use to rank performance levels for various systems and that evaluators could use to construct abstract models for large-scale force-on-force models.

There are no formalized testing procedures for measuring rollover propensity in the off-road environment. We propose using simulation tools to provide an initial measurement of off-road rollover propensity. The first task is to collect rollover statistics from vehicles maneuvering in terrain patches from typical off-road environments. Figure 8 illustrates three paths from the left side to the right side of a representative test patch. The contours of the test patch are shown in brown, and obstacles such as bushes or rocks are shown in green. The path that each vehicle drives is constrained by the waypoints, shown as large red circles in the figure. The exact path and the speed of travel are controlled by the planning algorithms or, in the case of a tele-operated system, by the operator. The top robot path is incomplete; the robot rolls over halfway along its intended path.

We need a simulation tool that has a detailed model of the vehicle undergoing test, a representation of the driver algorithm, and rich battlefield environment. Among the 14-DOF dynamics models, VDMS is the best choice because it can be easily linked with a distributed test environment. Also, it will continue to be improved as Cold Regions Research and Engineering

Laboratory (CRREL) and TARDEC's tire-soil interaction research matures. The distributed test environment is the most efficient way to include the driver algorithms. The simulation tools must be able to represent a variety of off-road environments containing tripping features such as rocks, ditches, and fallen logs. Variable friction coefficients and deformable surfaces will allow vehicles to slide into tripping features and sink into the terrain. A key model in the simulation tool is a model of the robotic perception system. Using a distributed simulation tool allows us to incorporate robotic perception models developed by other test centers or the system designer.

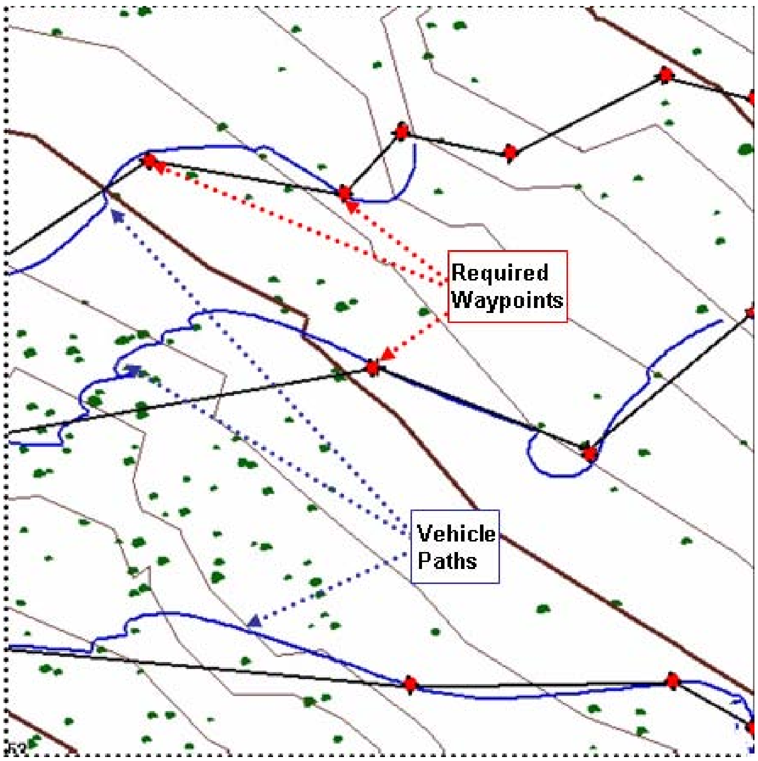

Figure 8. Three paths through a test field.

Simulation tools allow us to study vehicle rollover during combat scenarios in depth. By analyzing typical vehicles in battlefield scenarios, we can identify conditions and behaviors that lead to rollover. We can derive candidate rollover tests that are analogous to the NHTSA maneuvers, from instances of rollover and near rollover in the simulated vignettes that are relevant to actual vehicle use in battlefield scenarios. Potential tests can be simulated in a variety of battlefield environments to examine sensitivity and repeatability.

For specific robotic systems, simulation studies provide performance data in environments not addressed by physical tests. We can also identify minimum conditions to consistently cause rollover. The tester uses this information to set speed profiles, turn, and other factors so that physical tests provide usable information with the fewest possible runs.

10. Conclusions

The anti-rollover case study is the first of a series of case studies used to refine the RIEP process for developing tests and methodologies to evaluate robotic behavior algorithms. This particular case study enabled us to apply our current four-step RIEP process to a familiar problem for which much of the testing methodology had been previously developed for manned systems. In the first step, we conducted a thorough analysis of vehicle rollover using the extensive body of rollover literature from the transportation safety community. Vehicle rollover is an important topic in the transportation industry, so there are several papers discussing rollover mechanisms, prevention systems, and rollover testing programs.

The second step of the RIEP process is to find a simulation environment that is “rich” enough to simulate the task and test the proposed algorithm. Again, the automotive industry is an important source of information about the use of simulation tools to study the rollover issue. In this report, we discussed some of the commercial and Government vehicle dynamics simulation packages. However, the automotive industry’s primary interest is in rollovers on or near roadways. Modeling rollover in the off-road environment requires additional models for complex terrain surfaces and the robotic perception process. VDMS, a Government simulation tool, may be more suitable for the off-road environment. It uses a common terrain database format so that a variety of terrains can be easily investigated. VDMS also incorporates complex tire-soil interactions using on-going research models from TARDEC and CRREL. Unlike the commercial products, VDMS is already compatible with other simulation tools used in distributed simulation exercises.

In the third step of RIEP, we link a proposed rollover prevention system to the simulation environment. Currently, we do not have a proposed system, but several researchers have used simulation environments in their development process by linking a MATLAB rollover prevention algorithm to one of the vehicle dynamics simulation packages. It is possible to link an actual rollover prevention system to a simulation tool if vehicle attitude information such as roll or pitch is provided. This information must be transmitted from the simulated environment to the rollover prevention system.

The last step of RIEP is to design a set of meaningful tests and performance measures to evaluate a proposed rollover prevention system. In general, most of the tests designed to evaluate the rollover risk of passenger cars apply to unmanned vehicles. Laboratory measures such as the SSF and the CSV establish vehicle characteristics. Test track maneuvers can verify that an anti-rollover system functions in a benign environment. A useful metric to consider is rollover propensity which measures the likelihood that a system will roll in a single-vehicle accident. Unlike the transportation industry which has years of accident statistics, we do not have a lot of data on rollover accidents for robotic systems operating in the off-road environment. We

recommend a series of simulation studies to examine rollover propensity in the off-road environment.

Even this case study has uncovered differences between manned and unmanned system testing. Current approaches to rollover testing for manned systems concentrate on the contribution of the vehicle. For autonomous unmanned systems, the algorithms “driving” the vehicles must be tested as well. Maneuvers that require the robot to plan its path through a region test both the driver and the vehicle. Here again, simulated runs can supplement the information we can collect from physical test runs.

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